A TENSION OBSERVER AND NEURAL NETWORKS COMBINATION FOR REWINDING SYSTEMS

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Abstract: *A tension control problem of a rewinding web handling system is considered in the paper. It is shown that the dynamical response of the web handing system heavily depends on roll inertias. Dissimilar to other works that heavily based on the assumption of cylindrical roll form and roll aligment that leads to easy calculation of roll inertias, the main contribution of the paper is an introduction of a neural network to estimate varying inertias of unwinding and rewinding that cannot be directly computed. In addition, a tension controller based on backstepping controller without using tension sensor from the system. The tracking performance is shown through simulation results.*

Keywords: Roll to Roll System (R2R); Tension Observer; Radial Basis Function (RBF).

1. INTRODUCTION

Numerous practical applications ultilize web handling systems such as flexible displays, color-shifting, lighting, solar cells, etc. utilizing rewinding systems are becoming popular in industry [1-5]. After being processed, web is rolled up then is taken into the web-handling machines for further actions. The rewinding system exhibits strong nonlinearity and is affected by different types of noises, especially when the system is operating at high speed [2].

In order to properly handle the system, it is pivotal to formulate an approriate algorithm for the system. In web machining system, it is vital to regulate tension force in a desired region [6] to ensure the quality of materials. A variety of algorithms are introduced, including backstepping [7] and [8]. During the process of tension control, we need to measure different state variables and various parameters. In practice, it is tesious procedures with sensor mounting, signal calibrating,... during the process of measuring the response of tension force. Therefore, some in-depth researches on implementing feedback control based on the observation set [9] and [10] are carried out. It is evident that roll inertia information is essential for control system design [11] and [12]. Conventionally, the roll inertia depends on roll shape and web thickness. In practice, roll eccentricity and deformation exist and lead to false estimations. The robustness of the closed loop system against roll eccentricity is presented in [13]. However, when the parameters of the system are accompanied by system uncertainties, the proposed controllers can hardly guarantee efficiency and control quality in practice. Due to system uncertainties, it is a pivotal problem to develop an adaptive control to cope with the problem of varying roll inertia for the control of the R2R systems. A neural network is a powerful tool which can address the complex requirements of the system, requirements that other techniques could hardly solve. In this paper, by taking the advantages of the system equations of motion, a new control approach which uses tension observer integrated with an RBF neural network is proposed for the building of an R2R adaptive control system considering the presence of imperfection roll arrangements. The main contributions of the paper can be listed as: i) the proposal of the control scheme integrated with a tension observer, ii) the realization of an RBF based adaptive mechanism for compensating roll inertia uncertainties.

2. SYSTEM FORMULATION

A. R2R Web System Modeling

Figure 1 shows a single-span roll-to-roll web control system contains an unwinder and a rewinder. Input torques M_u, M_r are used to control web's velocity and tension.

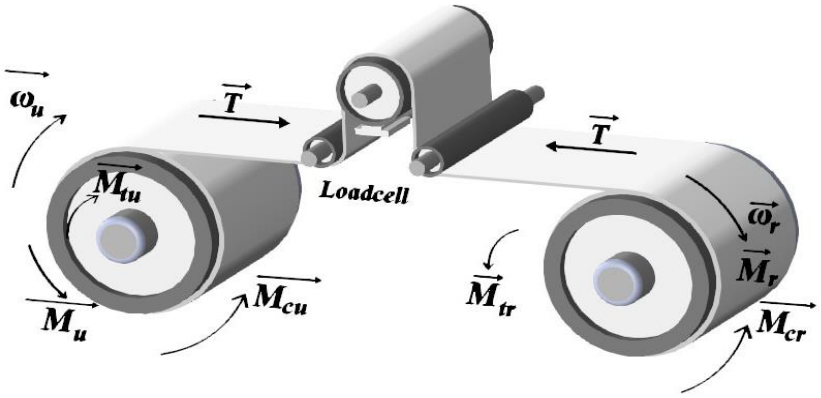


Fig. 1. *Single-span R2R web control system.*

Ignoring the influence of roll-web material slippage, material deformation, and the system friction. The dynamics equations can be given as follows:

$$\dot{T} = c_1\omega_u + c_2\omega_r T + c_3\omega_r \tag{1}$$

$$\dot{\omega}_u = c_4 M_u + c_5 T + c_6\omega_u + c_7\omega_u^2 \tag{2}$$

$$\dot{\omega}_r = c_8 M_r + c_9 T + c_{10}\omega_r + c_{11}\omega_r^2 \tag{3}$$

Where:

$$c_1 = \frac{R_u}{L}T_{\text{ref}} - \frac{ESR_u}{L}; c_2 = -\frac{r_r}{L}; c_3 = \frac{ESR_r}{L}$$

$$c_4 = -\frac{1}{J_u}; c_5 = \frac{R_u}{J_u}; c_6 = -\frac{b_{f_u}}{J_u}; c_7 = \frac{aw\rho R_u^{\ 3}}{J_u} - \frac{a}{2\pi R_u}$$

$$c_8 = \frac{1}{J_r}; c_9 = -\frac{R_r}{J_r}; c_{10} = -\frac{b_{f_r}}{J_r}; c_{11} = -\frac{aw\rho R_r^{\ 3}}{J_r} + \frac{a}{2\pi R_r}$$

The total moment of inertia and operating radius can be described as:

$$R_u(t) = R_{u0} - \frac{\theta_u a}{2\pi}; \quad R_r(t) = R_{r0} + \frac{\theta_r a}{2\pi} \tag{4}$$

$$J_u = J_{u0} + \pi\rho\omega\frac{\left(R_u^4 - R_{u0}^4\right)}{2}; \quad J_r = J_{r0} + \pi\rho\omega\frac{\left(R_r^4 - R_{r0}^4\right)}{2} \tag{5}$$

Where T: The web tension, J_u: The moment of inertia of the unwind roll and motor, J_r: The moment of inertia of the rewind roll and motor, R_u: The radius of the unwind roll, R_r: The radius of the rewind roll, B_u: The coefficient of vicious friction of the unwind roll, B_r: The coefficient of vicious friction of the unwind roll, E: The elasticity of web, S: The cross sectional area of web, L: The total length of web, a: The thickness of web, ρ: The density of web, w: The Width of web.

B. Tension observer based on backstepping controller

The controller aims at keeping the rewinding system tension and speed at the desired values. This section uses the sliding algorithm based on backstepping technique to design the controller. The design steps are as follows:

Step 1: Defining tracking error variables bellows:

$$\Delta T = T - T_d;\ \Delta\omega_u = \omega_u - \mathrm{W}_{ud};\ \Delta\omega_r = \omega_r - \mathrm{W}_{rd}$$

Step 2: Determining control signal such that web tension tracks the desired value. To regulate the error $\Delta T \to 0$, k_T is a positive gain, choosing W_{ud} w_{ud} as:

$$W_{ud} = -\frac{1}{c_1}\left(c_2 T\omega_r + c_3\omega_r - \dot{T}_d + k_T\left(T - T_d\right)\right) \tag{6}$$

Proposing a Lyapunov candidate function as:

$$V_1 = \frac{1}{2}\Delta T^2 \tag{7}$$

Using (1) and taking the time derivative of (7) we obtain:

$$\dot{V}_1 = \left(c_1\omega_u + c_2 T\omega_r + c_3\omega_r - \dot{T}_d\right)\left(T - T_d\right) \tag{8}$$

Next, replacing ω_u by W_{ud} w_{ud} that is determined in (8) results in:

$$\dot{V}_1 = -k_T\left(T - T_d\right)^2 \le 0 \tag{9}$$

Step 3: Base on backstepping technique, we will determine control signal M_u, M_r in order to ω_u track W_{ud} and ω_r track W_{rd}. Proposing Lyapunov candidate function as:

$$V_2 = V_1 + \frac{1}{2}\Delta\omega_u^2 \tag{10}$$

Differentiating (10) and using (2) gives:

$$\dot{V}_2 = -k_T\left(T - T_d\right)^2 + \left(c_4 M_u + c_5 T + c_6\omega_u + c_7\omega_u^2 - \dot{W}_{ud}\right)\left(\omega_u - W_{ud}\right) \tag{11}$$

The control signal is calculated as:

$$M_u = -\frac{1}{c_4}\left(c_5 T + c_6\omega_u + c_7\omega_u^2 - \dot{W}_{ud} + k_u\left(\omega_u - W_{ud}\right)\right) \tag{12}$$

Next, replacing M_u that is determined in (12) results in:

$$\dot{V}_2 = -k_T\left(T - T_d\right)^2 - k_u\left(\omega_u - W_{ud}\right)^2 \le 0 \tag{13}$$

Similarly, the control signal M_r is generated:

$$M_r = -\frac{1}{c_8}\left(c_9 T + c_{10}\omega_r + c_{11}\omega_r^2 - \dot{W}_{rd} + k_r\left(\omega_r - W_{rd}\right)\right) \tag{14}$$

In many cases, the use of tension sensors becomes expensive and difficult to install. To overcome this problem, in this paper we propose a tension observer. From (1) we can choose the tension observer that is determined by:

$$\dot{\hat{T}} = c_1\omega_u + c_2\omega_r\hat{T} + c_3\omega_r \tag{15}$$

Subtract (1) from (15) we obtain:

$$\dot{\hat{T}} - \dot{T} = c_2\omega_r(\hat{T} - T)$$

It is noted that $c_2\omega_r \le 0$ then $(\hat{T} - T) \to 0$ when time $t \to \infty$. In other words, observed tension $\hat{T}$ converge to actual tension value T.

With this observer, the control signals (6), (12), (14) are rewritten to:

$$\hat{\mathrm{W}}_{ud} = -\frac{1}{c_1}\left(c_2\hat{T}\omega_r + c_3\omega_r - \dot{T}_d + k_T\left(\hat{T} - T_d\right)\right) \tag{16}$$

$$\hat{M}_u = -\frac{1}{c_4}\left(c_5\hat{T} + c_6\omega_u + c_7\omega_u^2 - \dot{\hat{\mathrm{W}}}_{ud} + k_u\left(\omega_u - \hat{\mathrm{W}}_{ud}\right)\right) \tag{17}$$

$$\hat{M}_r = -\frac{1}{c_8}\left(c_9\hat{T} + c_{10}\omega_r + c_{11}\omega_r^2 - \dot{\mathrm{W}}_{rd} + k_r\left(\omega_r - \mathrm{W}_{rd}\right)\right) \tag{18}$$

C. Adaptive controller for uncertainties of the rewinding web system

Define W as the ideal weight and $\hat{\mathrm{W}}$ as the estimation of W. The error of ideal and estimated weights is defined as:

$$\tilde{\mathrm{W}} = \hat{\mathrm{W}} - \mathrm{W} \tag{19}$$

Then, J and $\hat{J}$ can be writen as:

$$J = W^T\underline{h};\ \ \hat{J} = \hat{W}^T\underline{h};\ \ \tilde{J} = \hat{J} - J = \tilde{W}^T h \tag{20}$$

Where $\underline{h}$ is the vector output of the hidden layer with its transfer function defined as:

$$h_i = \frac{\exp\left(-\dfrac{\left\|\omega_u - c_{1i}\right\|^2 + \left\|\omega_r - c_{2i}\right\|^2}{b_i^2}\right)}{\sum_{j=1}^{n}\exp\left(-\dfrac{\left\|\omega_u - c_{1i}\right\|^2 + \left\|\omega_r - c_{2i}\right\|^2}{b_j^2}\right)}$$

In which n is the number neural of neural network. With uncertain elements, control signals that are derterminded in the above section are rewritten as:

$$\hat{\mathrm{W}}_{ud} = -\frac{1}{c_1}\left(c_2\hat{T}\omega_r + c_3\omega_r - \dot{T}_d + k_T\left(\hat{T} - T_d\right)\right) \tag{21}$$

$$\hat{M}_u = -\frac{1}{\hat{c}_4}\left(\hat{c}_5\hat{T} + \hat{c}_6\omega_u + \hat{c}_7\omega_u^2 - \dot{\hat{\mathrm{W}}}_{ud} + k_u\left(\omega_u - \hat{\mathrm{W}}_{ud}\right)\right) \tag{22}$$

$$\hat{M}_r = -\frac{1}{\hat{c}_8}\left(\hat{c}_9\hat{T} + \hat{c}_{10}\omega_r + \hat{c}_{11}\omega_r^2 - \dot{\hat{\mathrm{W}}}_{rd} + k_r\left(\omega_r - \hat{\mathrm{W}}_{rd}\right)\right) \tag{23}$$

Proposing Lyapunov candidate function for the unwind roll as:

$$V_{eu} = \frac{1}{2}J_u\left(\omega_u - \hat{\mathrm{W}}_{ud}\right)^2 + \frac{1}{2}J_u\left(T - T_d\right)^2 + \frac{1}{2}J_u\left(\hat{T} - T\right)^2 + \frac{1}{2}Tr\left(\tilde{W}_u^{\ T}F_u^{-1}\tilde{W}_u\right) \tag{24}$$

Based on the derivative of the Lyapunov function, the updated law selected as:

$$\dot{\hat{W}}_u = -F_u\underline{h}\left[\left(\omega_u - \hat{\mathrm{W}}_{ud}\right)\dot{\hat{\mathrm{W}}}_{ud} - k_{u1}\left(\omega_u - \hat{\mathrm{W}}_{ud}\right)^2\right] \tag{25}$$

The proposed candidate Lyapunov function for rewind roll is:

$$V_{er} = \frac{1}{2}\left(\omega_r - \hat{\mathrm{W}}_{rd}\right)^2 + \frac{1}{2}\left(\hat{T} - T\right)^2 + \frac{Tr\left(\tilde{W}_r^{\ T}F_r^{-1}\tilde{W}_r\right)}{2J_r} \tag{26}$$

Similarly, the update law for neural network weight is chosen as:

$$\dot{\hat{W}}_r = F_r\underline{h}\left(\left(\omega_r - \hat{\mathrm{W}}_{rd}\right)\dot{\hat{\mathrm{W}}}_{rd} - k_{r1}\left(\omega_r - \hat{\mathrm{W}}_{rd}\right)^2\right) \tag{27}$$

3. SIMULATION RESULTS

In this section, the performance of the proposed controller is demonstrated through simulations. The parameters of the roll to roll system are utilized in simulation can be listed as follow: $R_{u0} = 0.04m$; $R_{r0} = 0.015m$; $J_{u0} = J_{r0} = 1kg.m^2$; $L = 0.3m$; $E = 2,5.10^9 N/m^2$; $Bu = Br = 0.00002533kgms/rad$; $a = 0.00002m$; $w = 1m$. In the simulation, fig. 2, fig. 3 and fig. 4 illuestrate the actual unwind and rewind rolls angular velocity, the tension response corresponding to desired web tension $T_{ref} = 10\,\mathrm{N}$.

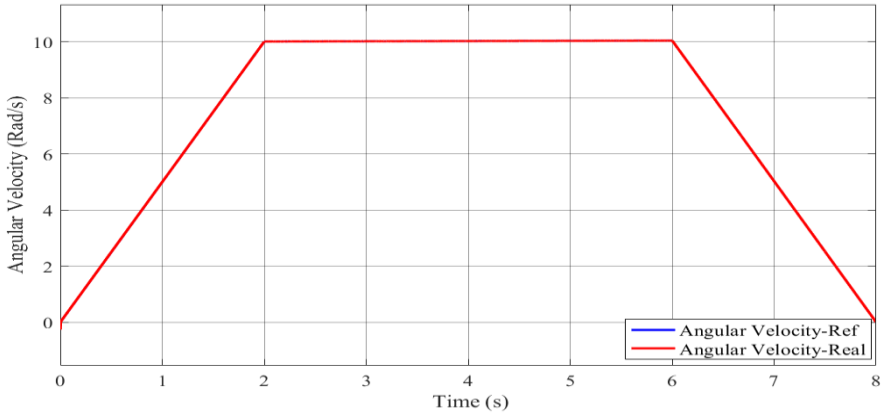


Fig 2. *Rotational angular response of the unwind roll.*

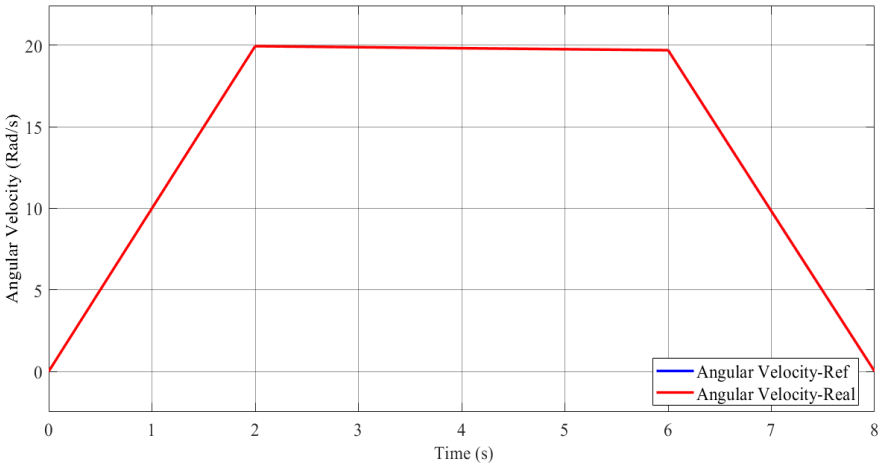


Fig 3. *Rotational angular response of the rewind roll.*

The simulation results show the correctness of the estimation algorithm using RBF neural network combined with tension observation. The results of this uncertainty component will be updated continuously as the basis for synthesizing control signals for the backstepping and RBF coordination controller for R2R system to make the control structure adaptable to uncertainty existing on the system.

With the proposed controller, velocity tracks the reference value with almost zero error. Fig. 2 and fig. 3 describe the angular velocity of the system, where the rewinder and winder angular velocity increase and decrase in accordane with roll radius variations. Fig. 4 shows the tension of the R2R. This study has given an advantage over the work given in [14] when no information about the operating roll moment of inertia is required.

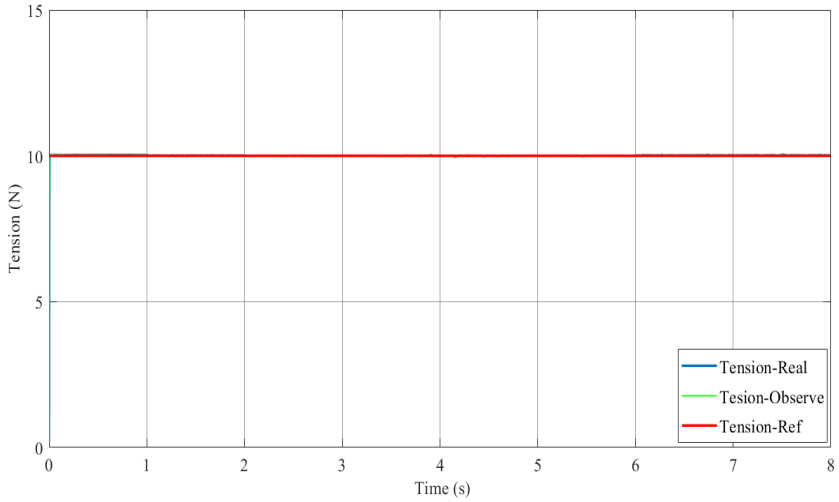


Fig 4. *The web tension response.*

4. CONCLUSIONS

In the paper, the tension controller is formulated thank to backstepping method integrated with the tension observer for the web transport systems. The RBF neural is utilized compensating system uncertainties caused by varying roll inertias. The numerical results indicate that the closed-loop system exhibits good tension tracking and adaptation performances. Furthermore, using RBF neural network, the controller does not require the precise description of the web system, thus the proposed controller is highly capable in various industrial applications.

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REFERENCES

[1]. K. Okada, T. Sakamoto, "*Adaptive fuzzy control for web tension control system*", 24th Annual Conference of the IEEE Industrial Electronics Society, Aachen Germany, August 31-September 4, (1998).

[2]. K. M. Chang, C. P. Weng, "*Modeling and control for a coating machine*", JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, Vol. 44, No. 3. pp. 656–661, (2001).

[3]. C. G. Kang, B. J. Lee, "*Stability analysis for design parameters of a rollto-roll printing machine*", International Conference on Control, Automation and Systems, Seoul, South Korea, October 17-20, (2007)

[4]. C. G. Kang, B. J. Lee, "*MIMO tension modelling and control for roll-toroll converting machines*", IFAC Proceedings Volumes, Vol. 41, No. 2, pp. 11877-11882, (2008).

[5]. T. Sakamoto, Y. Fujino, "*Modelling and analysis of a web tension control system*", IEEE International Symposium on Industrial Electronics, Dubrovnik, Croatia, July 10-14, (1995).

[6]. X.-L. Ding, W.-X. Zhang, M. Zhang, X.-M. Xu, and S.-H. Wei, "*Design and Analysis of a Novel Tension Control Method for Winding Machine*," Chinese J. Mech. Eng., vol. 31, no. 1, (2018).

[7]. K. H. Choi, T. T. Thanh, and D. S. Kim, "*A precise control algorithm for single-span roll-to-roll web system using the back-stepping controller*," IEEE Int. Symp. Ind. Electron., no. ISlE, pp. 1709–1714, (2009).

[8]. K.-H. Choi, T. T. TRAN, and D.-S. KIM, "*Back-Stepping Controller Based Web Tension Control for Roll-to-Roll Web Printed Electronics System*" J. Adv. Mech. Des. Syst. Manuf., vol. 5, no. 1, pp. 7–21, (2011).

[9]. M. Mahfouf, Y. Y. Yang, M. A. Gama, and D. A. Linkens, "*Roll Speed and Roll Gap Control with Neural Network Compensation*" ISIJ Int., vol. 45, no. 6, pp. 841–850, (2006).

[10]. P. D. Mathur and W. C. Messner, "*Controller development for a prototype high-speed low-tension tape transport*" IEEE Trans. Control Syst. Technol., vol. 6, no. 4, pp. 534–542, (1998).
[11]. F. Mokhtari, P. Sicard, "*Decentralized control design using integrator backstepping for controlling web winding systems*", 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, November 10-13, (2013).
[12]. J. K. Chen, Z. P. Yin, Y. L. Xiong, J. Z. Quan, "*A hybrid control method of tension and position for a discontinuous web transport system*", International Conference on Information and Automation, Zhuhai, China, June 22-24, (2009).
[13]. K. C. Lin, "*Observer-based tension feedback control with friction and inertia compensation*", IEEE Transactions on Control Systems Technology, Vol. 11, No. 1, pp. 109–118, (2003).
[14]. Thi, L. T., Tung, L. N., Duc Thanh, C., Quang, D. N., & Van, Q. N. (2019). *Tension Regulation of Roll-to-roll Systems with Flexible Couplings. 2019 International Conference on System Science and Engineering (ICSSE).*

TÓM TẮT

KẾT HỢP BỘ QUAN SÁT LỰC CĂNG VỚI MẠNG NƠ-RON TRONG ĐIỀU KHIỂN HỆ CUỘN LẠI

Vấn đề điều khiển độ căng của hệ cuộn lại được xem xét trong bài báo. Nghiên cứu chỉ ra rằng, động lực học của hệ thống xử lý phụ thuộc rất nhiều vào quán tính cuộn. Khác với các nghiên cứu khác dựa trên giả định về các cuộn có dạng hình trụ hoàn hảo, vật liệu có độ dày đồng nhất và các biến có thể được đo trực tiếp bằng cách sử dụng các cảm biến. Đóng góp mới của bài báo là việc trình bày mạng nơ-ron để ước tính mômen quán tính của lô tở và lô cuốn thay đổi tùy theo chuyển động của vật liệu và bộ quan sát lực căng dựa trên bộ điều khiển Backstepping mà không sử dụng cảm biến lực căng từ hệ thống. Hiệu suất theo dõi được thể hiện thông qua kết quả mô phỏng.

Từ khóa: Hệ cuộn lại (R2R); Bộ quan sát lực căng; Mạng nơ-ron (RBF).

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